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OBSERVATION OF CLEAVAGE FRACTURE AFTER SUBSTANTIAL DIMPLE RUPTURE IN ASTM A710 STEEL

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ABSTRACT

A major concern often arising in structural integrity predictions is the possibility that low-energy brittle fracture could result as a consequence of cleavage either under normal operating or design accident conditions. This can be especially troublesome when the leak-before-break (LBB) approach shows an additional safety margin of the design. For LBB to be applicable, the fracture process must remain ductile (dimple rupture), and not change to cleavage. The American Society for Mechanical Engineers Boiler and Pressure Vessel Code (Code) provides guidelines for avoiding cleavage fracture for Code-accepted materials. Experimental results for a non-Code steel are provided, and show that cleavage may occur for a thickness under16 mm (where the code suggests it will not) after stable crack growth (Δa) of up to 20 mm. This work is still in progress; test results are provided along with possible reasons for the mode transition, but complete explanations are still being developed.

INTRODUCTION

Cleavage fracture during crack growth initiation generally results in sudden, catastrophic structural failure, and must be avoided! Cleavage fracture after stable ductile crack growth is also a concern, but this transition has only been observed in limited cases where crack growth was less than 2 mm.[1,2] However, the possibility of a sudden fracture after stable crack growth has significant practical concerns. Steel structures, including pressure vessels, should certainly incorporate a fracture-resistant design. If cracks should appear and grow, the mechanism should be hole growth (ductile) rather than cleavage (brittle) to limit crack velocities and fragmentation. The need to reduce chances of cleavage fracture led to development of design procedures to prevent unexpected, sudden failure of structural components. Welding Research Council Bulletin 175[3] provides these procedures, based on the requirement that the minimum operating temperature will exceed the material's "transition temperature." This corresponds to a fracture mechanism change from cleavage (low absorbed energy) to ductile hole growth (high absorbed energy). The approach requires drop weight tests (per ASTM E208-69), when geometrically possible, to obtain the transition temperature (T_{NDT}), and Charpy V-notch (CVN) impact tests when the material thickness exceeds 16 mm.

NB-2332 of the Code[4] provides guidelines for the minimum operating temperature relative to CVN impact results. Minimum specified CVN values are required at test temperatures less than or equal to the lowest desired material service temperature. Thin materials (<16 mm) have no requirement, and intermediate thickness have a minimum CVN lateral expansion requirement. Plates thicker than 63.5 mm have a minimum absolute operating temperature (RT_{NDT} + 56°C) specified. Thus, the ability to design structural components to prevent non-ductile fracture appears to be established simply by following these requirements.

The Leak-Before-Break (LBB) approach to fracture-resistant design was originally developed by Irwin[5] to establish the required fracture toughness to prevent crack growth when a material was loaded to the yield strength. In the late 1970s, LBB was extended (required fracture toughness such that a through-thickness crack, twice as long as the material thickness, will not extend unstably – corrosion-enhanced growth excluded). This suggested that, if a crack penetrated the wall thickness of a vessel pressurized with a fluid, and the crack length was less than twice the wall thickness, then the vessel would simply leak, hence, "leak-before-break." Further, such a vessel would not experience catastrophic failure until additional crack growth occurred. During the time that the crack leaks, it is assumed that the leak will be detected and remedial measures performed before the crack reaches a critical size. Therefore, by following this hypothesis, it would be possible to predict conditions where LBB would apply. In those cases, LBB can be a safety mechanism of last resort to detect a significant crack before unstable fracture occurs. The LBB concept of pressure vessel safety is now used throughout the world.

This paper provides experimental results from surface crack test specimens (simulating the fracture behavior of structural components). Cleavage fracture occurred in the experiments when the Code sugests it will not. Through careful examination and critical analysis of these results, we hope to better understand factors controlling cleavage fracture following stable ductile tearing. This will help provide solutions to practical problems associated with applying LBB concepts to structural safety.

MATERIAL CHARACTERIZATION

The A710 steel used in this study is not explicitly qualified by the Code. But, the A710 steel showed the unexpected cleavage transition behavior of interest, and a large database of material properties and experimental data already exist that will aid in analyzing the phenomenon. Therefore, for purposes of comparison and analysis, the intent of the Code relating to material properties was applied.

The thickness of the A710 steel plate was 31.8 mm. The specimens containing surface cracks were either 6.4 or 12.7 mm thick, and they were removed from the central plate thickness. The chemistry of the A710 steel is: 0.05 C, 0.47 Mn, 0.010 P, 0.004 S, 0.25 Si, 0.74 Cr, 0.85 Ni, 0.21 Mo, 1.20 Cu, and 0.038 Cb with an ASTM grain size of 8. ASTM E208,[6] P-3 NDT tests were performed on the 31.8 mm thick steel plate. The results showed that T_{NDT} is -18°C (0°F) for plate C12188. CVN impact tests were performed per ASTM E23[7] with the specimens oriented in the transverse (T) direction.

A number of specimens containing surface cracks with a/t ranging from 0.15 to 0.85 and a/2c ranging from 0.1 to 0.5 were tested. Data collection included: stop-action photographs at the front and back surfaces; acoustic emission; applied force, crosshead displacement, and crack mouth opening displacement (CMOD); and the applied force when the growing crack penetrated the opposite surface. (penetration was identified using a rubber air bulb held to the back surface by vacuum; it fell off when air passed through the opening at crack penetration, releasing the vacuum.)

TEST RESULTS FOR SURFACE CRACKED SPECIMENS

We have observed that surface cracks grow predominantly through the thickness direction, with little or no growth in the plate width (2c) direction. Once the crack penetrates the back surface, it then

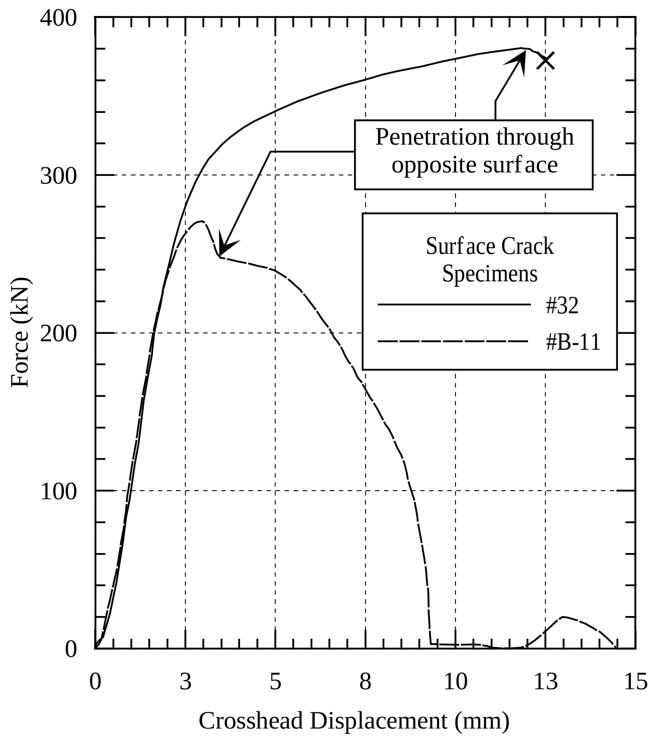

Figure 2. Test record for two surface crack specimens.

grows until the length at the back surface is the same as the length at the front surface. The crack growth to this point is essentially dimple rupture occurring in the plane of the original fatigue precrack. As the test progresses, the specimen configuration is analogous to a middle crack [M(T)] specimen. The crack growth then transforms to a single- or double-slant fracture. Stable crack growth continues until either the crack tip reaches the specimen edge, or sudden cleavage fracture results in catastrophic specimen failure. Figure 1 shows force vs. crosshead records for Specimen 32 (experienced cleavage fracture at both crack tips) and for Specimen B-11 (did not experience cleavage). Figure 2 shows the fracture surfaces of specimens (#15, #B-42) that experienced cleavage fracture. It is apparent that the amount of stable crack growth preceding catastrophic failure varied considerably (ranging from a few mm, up to 20 mm), and that the transition from ductile fracture to cleavage was abrupt. The fracture surfaces of these specimens were examined by light microscopy, and with SEM, and only a few islands of cleavage were detected behind the main ductile/cleavage boundary. These isolated islands were small (~30 µm) and occurred infrequently. Figure 2 suggests that there is almost a straight line of transition separating dimple rupture from cleavage.

Recently, another series of specimens (B-24, B-29, B-43, C-6, C-23, and E-14) were tested. Of the six specimens, four experienced cleavage (B-29, B-43, C-23, and E-14). Figure 3 shows the fracture surface for Specimens B-29 and B-43.

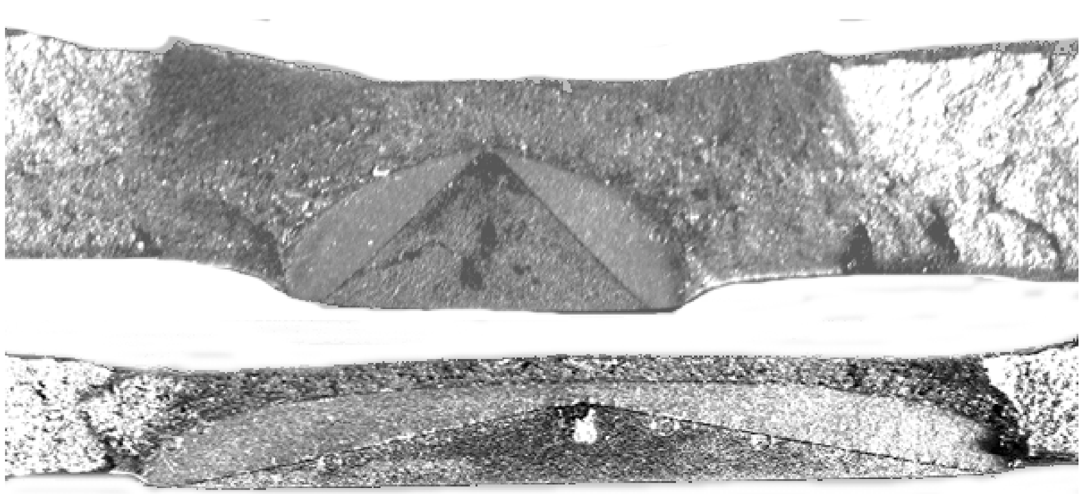

Figure 1. Fracture surfaces of specimens #B-42 (above, 12.7 mm thick) and #15 (below, 6.4 mm thick) tested in mid-1980s. Transition from ductile (darker) to cleavage (brighter) fracture is visible. Note chevron shape of transition boundary at left on #15.

Figure 3. Specimen B-43 (above) and B-29 (below). Darker, crescent-shaped region extending to back surface on B-43 is ductile fracture region. Cleavage on B-29 is isolated to far left and right.

DISCUSSION

CVN Results: T_{NDT} is -18°C (0°F) for plate C12188 of A710 steel. The steel's 0.89 mm lateral expansion at 24°C easily exceeds the Code requirement of 0.64 mm for materials up to 38.1 mm thick. Therefore, the test results at 24°C determined the minimum "operating" temperature. At 24°C the CVN impact energy results for the transverse-oriented (L-T) specimens were 62, 62, and 87 J with corresponding lateral expansion of 0.94, 0.94, and 1.24 mm. Therefore, applying the "intent" of the Code, the minimum operating temperature was set to be 24°C. Reference 3 notes that energy absorption (higher measured CVN energy) may be increased by increasing material yield strength or ductility. Of these, ductility (associated with CVN lateral expansion) is a better indicator of fracture toughness change. For this material, the measured lateral expansion of 0.94 mm exceeds the Code-required values, and is a positive indicator that the material meets the minimum Code-inferred fracture toughness. Another item of possible concern is that the CVN specimens had only 10% shear fracture area at 24°C. However, this parameter is not considered in the ASME Code.

Surface Cracked Specimens: Figures 2 and 3 clearly show that cleavage did not occur until after the surface cracks had penetrated the back surface and were growing in the plate width (2c) direction. In many instances, the cleavage fracture initiated from 45 deg ductile, slant fracture, e.g. #B-29. In one of the fracture surfaces studied extensively in the SEM (Figure 2, B-42), there is a distinct, uninterrupted boundary separating ductile and cleavage fracture zones. There are only a few islands of cleavage in the dominantly ductile region, and they are located close to the transition boundary. It is commonly accepted that the probability of cleavage fracture initiation is modeled by a Weibull-type continuous probability function. The model uses a critical cleavage stress and a representative material length as its governing parameters for a particular material. The probability of cleavage fracture initiation, at any location in the volume being considered, for a given crack boundary and stress state in that same volume, is calculated through volume integration of principal stresses near the crack boundary. For a given material, a longer crack boundary (specimen/crack size effect) or higher principal stresses (material strength/hardening influence and applied loading) can increase the probability of cleavage fracture initiation. This model is limited to predicting the probability that cleavage fracture will initiate at any instant at some point within the volume of material considered. The so-called weakest link model of macroscopic cleavage fracture assumes that an individual initiation will always progress to a macroscopic fracture event. However, if cleavage fracture does initiate, whether or not it will continue beyond the grain in which it initiates is not an explicit model output, since the material stress state has changed. In addition, the model does not explicitly predict the likelihood that cleavage fracture will initiate simultaneously at multiple locations in the volume under consideration.

Gerberich et al.[8] extend this probablistic cleavage initiation concept to macroscopic cleavage crack growth. They suggest that sustained cleavage crack growth (following initiation) may very likely be the result of multiple cleavage initiation events occurring almost simultaneously. The various distinct cleavage islands then grow together to sustain the macroscopic cleavage fracture process. In effect, they acknowledge the validity of the Weibull model for cleavage initiation, but reject the weakest-link assumption for continuing macroscopic fracture. Gerberich's suggested crack growth process was strongly supported by INEEL's surface crack test results. For example, extensive examination of the fracture surface of specimen B-42 showed "river patterns" (chevron-shaped features) on the cleavage region pointing back to numerous initiation sites along the ductile/cleavage fracture boundary. Other specimens show isolated islands of cleavage fracture embedded within the ductile fracture region. These are sites where cleavage initiated, but most likely arrested due to insufficient driving energy. Certainly, the weakest link assumption provides a useful boundary to application of the Weibull PDF where cleavage fracture is to be avoided. However, it is a rather severe restriction when it comes to fracture process modeling. The real crack growth process observed in experiments is not allowed by the "weakest link" stipulation.

It may be possible to extend the Weibull probability model to estimate the likelihood of a macroscopic cleavage fracture event arising from essentially simultaneous multiple initiations. But, the complexities of the process make the job enormous. The fracture process volume must be discretized to small volume elements, and the associated stresses determined using FEM. Then, an iterative probability simulation considering all possible outcomes must be performed. We hope that the INEEL microtopography fracture process analysis system will provide additional information on crack boundary locations at various points in the fracture process. This will eliminate a very tedious and still very difficult 3-D plastic crack growth modeling process, and reduce some uncertainty in the model associated with predicting crack growth. Rather than calculating crack growth increments based on some estimated criteria (which may not match the actual specimen behavior), incremental crack boundary positions can be specified based on experimental data. We also hope to establish at what point (crack boundary position, applied remote load) some of the isolated cleavage islands were generated. This will be accomplished through the correlation of engineering test data (force, displacement, COD, etc.), acoustic emission monitoring data, electric potential crack growth monitoring data, and microtopography-determined crack boundary locations.

At the present time, test data exists from a variety of A710 steel surface crack specimen geometries. Some specimens exhibited sudden catastrophic failure after little ductile crack growth, others after a large amount of ductile growth, while others experienced plastic instability with no cleavage at all. Various test parameters, such as test machine and specimen compliance, crack growth rate, specimen thickness, and initial surface flaw configurations were examined for correlation with the crack growth behavior. No correlation with observed crack growth behavior was found.

Specimen E-14 (a recent surface crack test) exhibited a double 45 deg slant fracture with a central flat region that was nominally triangular in shape, with mostly ductile fracture appearance. Point sources of specular light reflection from small cleavage facets were observed in this flat region. However, considerable ductile crack growth occurred before the transition to cleavage. Specimen B-24, also tested recently, exhibited a single 45 deg slant fracture. Light reflection from a section that went completely through the thickness (see Figure 4) shows that cleavage fracture occurred in this region. These types of cleavage regions were not observed in the first series of surface crack tests performed in the mid-1980s. We presently have no guess why these regions of cleavage did not cause catastrophic failure of the test specimens. We also do not have a qualified explanation for the difference in fracture behavior of recent tests compared to those performed some 15 years ago.

Our best hypothesis at present includes two inter-related factors for the surface crack specimens. First, crack tip constraint varies significantly during the fracture process. Second, plastic deformation of the material far ahead of the original crack (pre-straining) creates an effective yield strength increase before the fracture process zone reaches those locations (also assisting in elevation of local constraint). Reuter et al.[9] show that differences in constraint exist between specimens containing surface cracks and SE(B) specimens. In all surface crack specimens (that had some cleavage) that have been examined, the cleavage events initiated in the central portion of the specimen thickness. Constraint is known to be higher there than nearer the specimen surface. Further, the maximum local stress intensity, K (or local J-integral), obtained from FEM analysis methods for surface cracks, does not occur at a corresponding location. Crack initiation studies indicate that local maximum driving force, K[9] (or J[2]), alone do not dictate the crack initiation location, but that some (yet to be defined) critical combination of crack driving parameter and constraint measure (e.g. K and T or J and Q)[9,2] control the fracture initiation process.

We also noted that cleavage fracture did not occur until the surface crack penetrates the opposing surface. Reduced constraint on the crack perimeter due to plastic flow to the opposing surface is a likely cause. The critical stress level required to initiate cleavage cannot, therefore, be reached. Once the crack penetrates the thickness and is growing parallel to the plate surface, the local constraint probably increases due to several factors[1] until the critical condition for cleavage initiation can be reached. Green and Hundy[10] note that pre-straining a material increases its yield strength, causing the ductile-

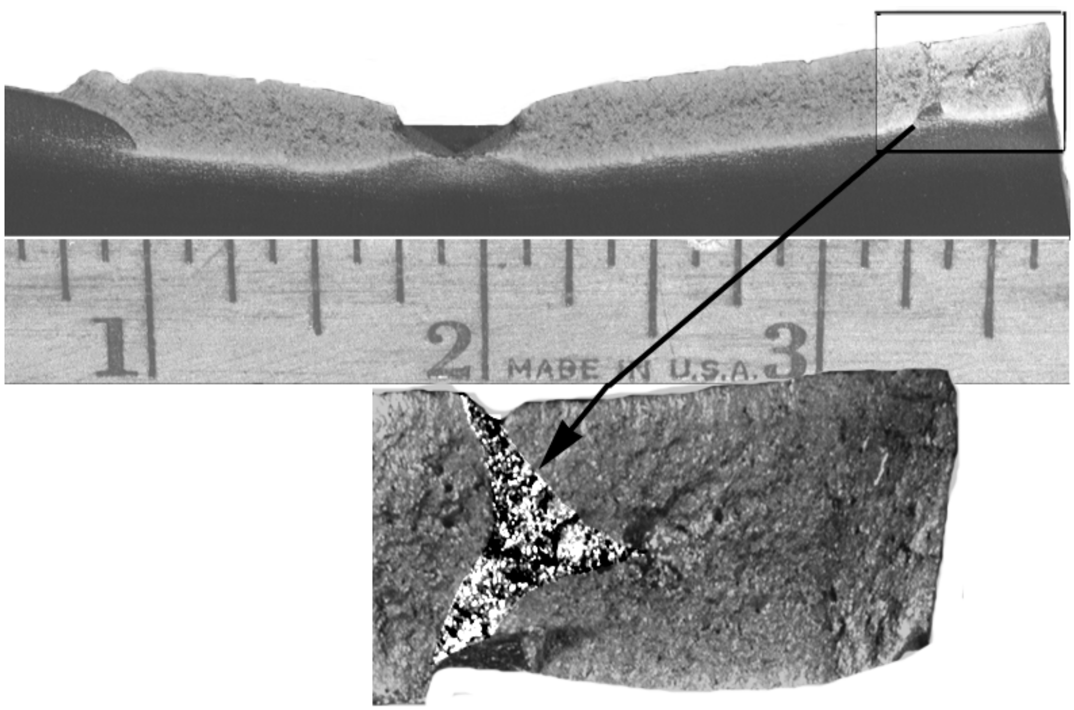

Figure 4. (a) Specimen B-24 fracture surface (inch scale). (b) Inset, magnified, showing band of cleavage traversing the specimen thickness.

brittle transition temperature to increase. At a given temperature, this will increase the probability of brittle cleavage fracture occurring. M(T) plate specimens of the same A710 steel (tested in the mid-1980s) do not undergo as much material pre-straining as the surface crack specimens, and they never had a cleavage fracture. This infers that the level of material pre-straining (in the surface crack specimens) plays some role in the ductile-to-cleavage fracture mode change. Dodds et al.[2] also note that crack tip meandering (out of the nominal crack plane) associated with ductile crack growth has a substantial effect on the stress fields at the crack tip.

The difference in behavior (observed cleavage regions) between specimens tested recently and those tested about 15 years ago may be explained by a change in the material's sensitivity to constraint. The percentage of cleavage fractures experienced in the recent test series appears to be about twice that of the earlier tests. This difference may be real which would mean that embrittlement occurred while the test specimens have been in storage at nominally 24°C. This may be due to a room temperature aging phenomenon, which we feel is unlikely, but that is yet unproven. To evaluate this possibility, the grip section (only elastically strained) of some of the recently tested specimens were machined into CVN specimens. They were impact tested, and lateral expansion exceeded 1.6 mm at 24°C. Comparison of recent CVN test results with original material certification data (1981) suggests that: T_{NDT} is unchanged; the transition region slope is now steeper (narrower temperature range); and fracture energy (CVN) is elevated. These results, obtained just a few days ago, are contrary to what was expected based on the recent surface crack tests. Because of these conflicting results, we have no explanation for the change in observed behavior of the surface crack specimens. We are planning additional tests and analyses to unravel the mystery of this apparent material change.

At this time, we can draw the following conclusions:

(1) Catastrophic cleavage fracture can occur after a surface crack has penetrated the opposing surface when the plate thickness is less than 16 mm, even after ductile crack growth (by hole growth/dimple rupture) has progressed over 20 mm;

(2) Catastrophic cleavage fracture can occur even when the test temperature equals a temperature where the Code requirement for minimum lateral expansion in a CVN test is exceeded;

(3) Comparison of Charpy impact (CVN) test results, from the same heat of material but measured 18 years apart, show substantial differences. The more recent results suggest cleavage fracture should not occur, while the surface crack tests result in more observed cleavage;

(4) We cannot explain the sudden transition from ductile fracture to cleavage that occurs in the surface crack specimens, but recommendations for future work to study the phenomenon are as follows:

RECOMMENDED ACTIONS

(1) Calculate (via FEM) the stress fields, and corresponding constraint, at the front of the growing cracks for C(T), SE(B), and surface cracked (SC) specimens. Experimental methods will be used to establish incremental crack front positions, CTOD, and CTOA for input to the FEM;

(2) Test additional surface crack specimens (crack geometries and plate sizes) to replicate all configurations that were tested in the mid-1980s for comparative purposes;

(3) Tests of middle crack plate [M(T)] specimens for comparison with recent surface crack test results, and with earlier M(T) and surface crack results;

(4) Perform tensile tests of the A710 steel over a range of temperatures for comparison with original tensile data (1981);

(5) Use tensile or notched bend specimens to measure the critical cleavage stress of the A710 in its present condition; and

(6) Continue SEM studies to identify structure features responsible for initiation of cleavage fractures.

These tests and analyses will help us understand the substantial differences between the earlier (1981) and recent (2000) CVN test results, and the role these differences play in the sudden transition from ductile fracture to cleavage fracture.

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REFERENCES

(1) Faleskog, J. (1995), Effect of Local Constraint Along Three-Dimensional Crack Fronts – A Numerical And Experimental Investigation, **J. Mech. Phys. Solids, 43**(3), pp. 447-493.

(2) Dodds, R. H., Jr., M. Tang, and T. L. Anderson (1993), *Effects of Prior Ductile Tearing on Cleavage Fracture Toughness in the Transition Region*, **UILU-ENG-93-2014**, Department of Civil Engineering, University of Illinois, Urbana, Illinois, November 1993.

(3) PVRC Ad Hoc Group on Toughness Requirements (1972), *PVRC Recommendations on Toughness Requirements for Ferritic Materials*, **WRC Bulletin 175**, August 1972.

(4) NB-2330, Section III, Division 1-NB (1998), **ASME Boiler and Pressure Vessel Code**, 1998 Ed.

(5) Irwin, G. R. (1964), *Structural Aspects of Brittle Fracture*, **Applied Mat'ls Res, 3**, April 1964, p. 65.

(6) ASTM E208-91 (1993), *Standard Test Method for Conducting Drop-Weight Test to Determine Nil-Ductability Transition Temperatures of Ferrite Steels*, **1993 Annual Book of ASTM Standards, Volume 03.01**, American Society for Testing Materials, Philadelphia, PA, pp. 374-385.

(7) ASTM E23-93 (1993), Standard Test Methods for Notched Bar Impact Testing of Metallic Materials, ibid., pp. 206-226.

(8) Gerberich, W. W., S.-H. Chen, C.-S. Lee, and T. Levine (1987), *Brittle Fracture: Weakest Link or Process Zone Controlled?*, **Metallurgical Transactions A, 18A**, November 1987, pp. 1861-1875.

(9) Reuter, W. G., J. C. Newman, Jr., J. Skinner, and M. Mear (2000), Use of K_{Ic} and Constraint to Predict Location and Load Corresponding to Initiation of Crack Growth for Specimens Containing Surface Cracks, **32nd National Symposium on Fatigue and Fracture** (accepted for publication), West Conshohocken, PA, June 2000.

(10) Green, A. P. and B. B. Hundy (1956), *Initial Plastic Yielding in Notch Bend Tests*, **J. Mech. Phys. Solids, 4**, pp. 128-144.